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A spectral survey of the Orion Nebula from 455–507 GHz

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Abstract. The results of a submillimetre wavelength spectral line survey between 455.1–507.4 GHz of the Orion-KL hot cloud core are reported. A total of 254 lines were detected to a main beam brightness temperature sensitivity $T_{\text{mb}} \sim 1\text{--}3$ K. The detected lines are identified as being associated with 30 different molecular species or their isotopomeric variants. The strongest line detected was the $J = 4\text{--}3$ transition of the CO molecule. Apart from abundant diatomic rotors such as CO and CS, the spectrum is dominated by SO, SO₂ and CH₃OH and large organic molecules such as (CH₃)₂O, CH₃CN, C₂H₃CN, C₂H₅CN and HCOOCH₃ which make up $\sim 72\%$ of the total number of lines; unidentified lines $\sim 13\%$; and other lines the remaining $\sim 15\%$ of the total. Rotational temperatures and column densities derived using standard rotation diagram analysis techniques were found to range from 70–300 K, and $10^{14}\text{--}10^{17}$ cm² respectively.

Key words. molecules – star formation – molecular cloud

1. Introduction

The chemistry of the Orion-KL molecular cloud core has been better studied than that of any other massive star formation region in the Galaxy (high spectral resolution spectroscopic surveys have been carried out by a number of authors including: 72–91 GHz Johansson et al. 1984, 70–115 GHz Turner 1989, 138–151 GHz Lee et al. 2001, 150–160 GHz Ziurys & McGonagle 1993, 215–247 GHz Sutton et al. 1985, 216–242 GHz Blake et al. 1986, 247–263 GHz Blake et al. 1987, 257–273 GHz Greaves & White 1991, 330–360 GHz Jewell et al. 1989, 325–360 GHz Schilke et al. 1997, 342–359 GHz White et al. 1986, 334–343 GHz Sutton et al. 1995, 607–725 GHz Schilke et al. 2001, 780–900 GHz Comito et al. 2003, 190–900 GHz Serabyn & Weissstein 1995). Spectral line surveys can provide an unbiased view of the molecular constituents of the gas in star forming regions, and may be used to estimate the physical and chemical environment. We report here the first high spectral resolution survey in the 600 and 650 μm atmospheric windows between frequencies of 455 and 507 GHz.

2. The data

The spectral line survey was made using the James Clerk Maxwell telescope in Hawaii during October 1993 over the frequency range 455.1–507.4 GHz. This survey extended across most of the two atmospheric transmission windows near 650 and 600 μm . These windows are bracketed by strong telluric H₂O absorption lines, and their transparency is highly dependent on the line of sight water vapour column. The data were collected using the JCMT facility receiver, Rx C, operated in double-sideband mode. The adopted “on-source” position was that of the “hot core” close to IRc2 (α, δ)₁₉₅₀ = 5^h 32^m 46^s.9, $-5^\circ 24' 23''$. The pointing accuracy was measured to be good to better than 2'' rms, from observations of planets and compact calibrator sources used as standards at the telescope.

The half power beam width and main beam efficiencies of the telescope were measured from observations of Mars, Jupiter and Uranus. These ranged from 11'' and 0.53 at the low frequency end of the spectral region to 10'' and 0.49 at the upper end of the band. The receiver double sideband system noise temperatures were typically 1000–3000 K. The IF frequency was 3.94 GHz, and the spectra were processed using the JCMT facility 512 MHz bandwidth acousto-optical spectrometer, giving an effective spectral resolution of ~ 0.6 km s^{−1}.

The spectral region was covered by stepping the local oscillator in 100 MHz steps across the whole spectral region – so that any part of the spectrum was redundantly observed at least four times (i.e. at least twice in each sideband – and in many cases more times). Each observation consisted of a 4–10 min integration (total on and off source), which was carried out in a “position-switched” mode, where the telescope was alternated between the on-source position, and a “reference position” located 2100'' to the north. Previous observations of this “reference position” have shown it to be free of significant molecular emission intense enough to affect the accuracy of the survey. The reference position was checked by position switching the telescope against several other positions that were located more than 10 degrees away from the Galactic Plane – and not known to be associated with the locations of any molecular clouds or enhanced interstellar extinction. The spectra were calibrated channel by channel using the standard JCMT three temperature chopper calibration scheme (hot and cold loads and the atmosphere). Observations of the sideband gains were measured by observations of spectral lines that were present in both sidebands. The main beam brightness temperature noise levels varied from 1–4 K in a 2 MHz channel ($\sim 1.3 \text{ km s}^{-1}$).

During the data reduction, we attempted to recover an estimate of the single-sideband spectrum, using data collected with a double-sideband receiver. A difficulty common to sideband-deconvolution techniques is the uniqueness of the deconvolution given the observational factors such as pointing reproducibility, sideband gain imbalances, variable calibration solutions as sky conditions change and contamination or blending with strong lines (of both terrestrial and extra-terrestrial origin) in the opposite sideband. A deconvolution technique was used that separated out the emission into the individual sidebands. The basis of this technique (which has been widely used by many observers at the JCMT and forms part of the facility software – although this paper gives the first description of the algorithm that is used) is to set up a series of linked equations for each channel in the DSB spectrum. The first equation simply describes that the DSB line temperature is the sum of two intensities, one from the upper and one from the lower sideband (T_u and T_l , say). The second equation refers to the same spectral channel but with a shift in the local oscillator setting by $\Delta\nu$: the DSB signal is then the sum of T_u and $T_{l+2\Delta\nu}$, if we consider the upper sideband to be the frame of reference and the shift to be positive (increased frequency). Similarly we can consider the lower sideband to be the frame of reference, and obtain a third DSB signal that is the sum of $T_{u+2\Delta\nu}$ and T_l . This equation set can be extended as far as desired by taking any of the line frequencies offset by $2\Delta\nu$ and establishing which upper and lower sideband frequencies contribute to the observed DSB signal. The result is always to establish a set of n equations with $(n + 1)$ variables that are linked to a particular channel of the DSB spectrum. A solution can only be found where one of the $T(\text{DSB})$ is consistent with zero within the noise level of the observations. Since this implies (if there are no absorption lines) that both T_u and T_l are also zero within the noise, the equation set reduces to $(n - 1)$ unknowns and two known values – hence all n equations can be solved. In the present survey, the local oscillator was stepped in 100 MHz intervals, and the number of

equations used per spectral channel was typically 4–5. For several spectrally crowded regions, additional spectra were taken with different local oscillator offsets to improve the reliability of the deconvolution.

Multiple coverage of individual parts of the spectrum provided sufficient redundancy to allow single sideband spectra to be reconstructed, achieving an acceptable solution at most frequencies. The veracity of the technique could also be checked as lines from the lower and upper sidebands move in opposite directions in the DSB spectrum as the local oscillator frequency is stepped (in 100 MHz intervals). The deconvolution technique worked acceptably for more than 98% of the whole spectral range covered, but the remaining $\sim 2\%$ could not be solved because there was no signal consistent with zero in the DSB signal-set. A greater number of solutions could be found by extending the number of linked equations, but since the solutions are already of the form of sums and differences of DSB signals, the noise level will be increased if more differencing is involved. It is also inherent in the technique that there are a choice of solutions (for n equations and $(n - 1)$ unknowns), so we have adopted the minimum SSB results and an initial DSB signal $\leq 2\sigma$ for the “consistent with zero” DSB criterion. This minimises the level of spikes and should ensure that temperature solutions are underestimated by less than $\approx 3\sigma$. The locations of the parts of the spectrum for which we did not achieve a good deconvolution, are shown as horizontal bars under the spectrum in Figs. 3–6. We also visually inspected at the locations in a spectrum where bright lines from the opposite sideband might have left small residual artifacts (sometimes known as “ghost features” – Schilke et al. 1997), as well as inspecting the emission in the opposite sideband to the locations of all of the “U-lines”.

3. Data analysis

The intention of this paper is to present the data and some basic results. The spectrum shown in Fig. 1 is crowded with many blended lines, and in many places is confused – reflecting the rich and complex chemistry. A total of 254 lines were identified, although there may be more lines than this blended together. The lines were clearly identified using the JPL Sub-millimetre spectral line catalogues of Pickett et al. (1995), Pearson et al. (1996, 2000), Müller et al. (2000) and other lists of line frequencies referred to later in this paper. A total of 98 lines (32% of the total) could not be associated with known molecular transitions and have been designated as U-lines. Although it is possible that some fraction of these may be artifacts of the deconvolution process – the fact that they are distributed throughout the survey, and do not tend to congregate in areas where the deconvolution process was not successful, it is likely that many of these are real. Table 1 gives a breakdown of the number of transitions observed from each of the known species.

These data were used to estimate the rotational temperature, T_{rot} , and column densities, N_{col} , of the various species using the relationship given in Eq. (1).

$$\ln\left(\frac{3kc \int T_{\text{mb}} dV}{8\pi^3 \mu^2 \nu^2 S}\right) = \ln\left(\frac{N_{\text{T}}}{Q(T_{\text{rot}})}\right) - \frac{E_{\text{u}}}{kT_{\text{rot}}} \quad (1)$$

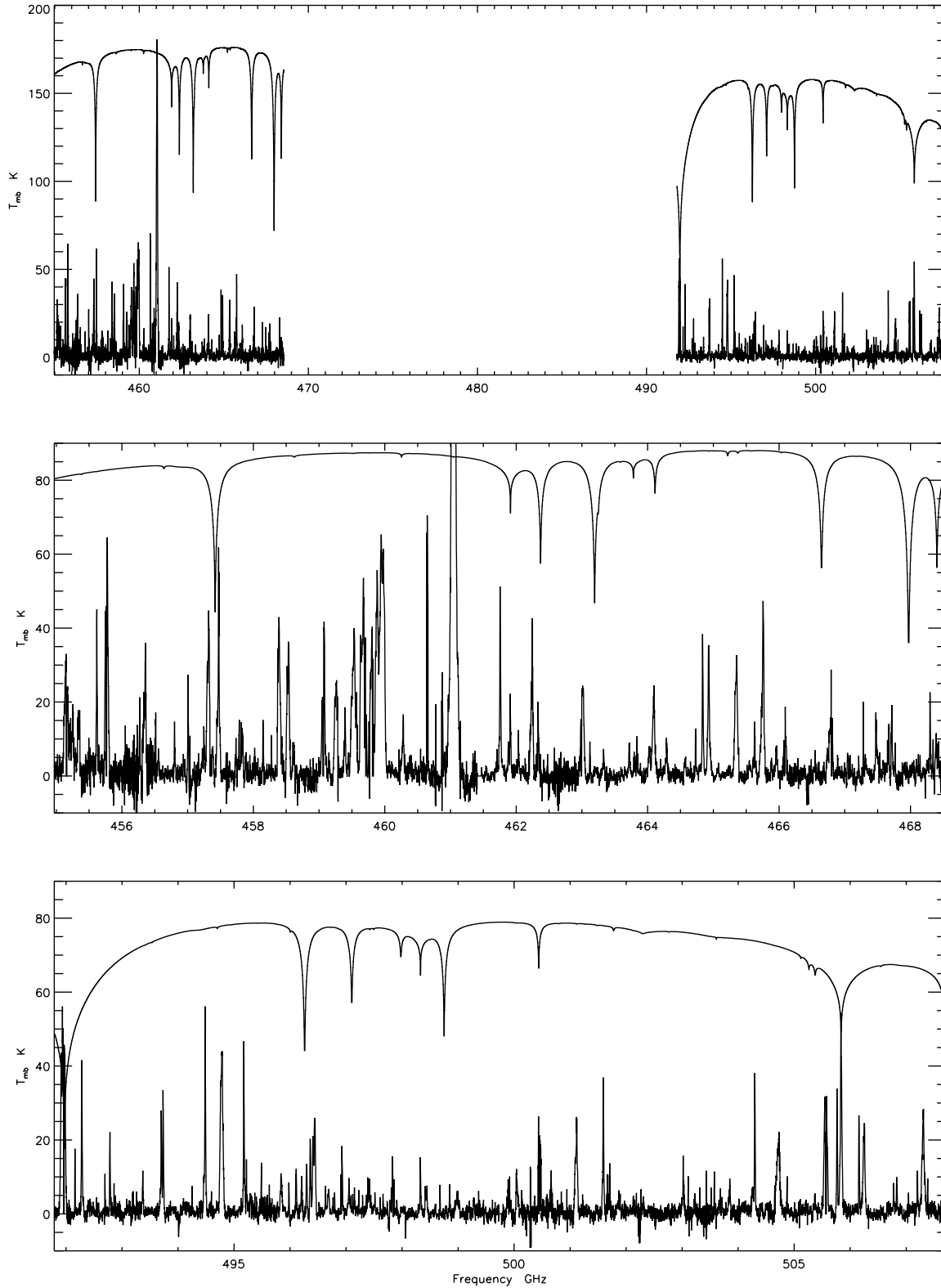


Fig. 1. The complete spectrum binned in 2 MHz channels in main beam brightness temperature units. A low order polynomial baseline was removed from some of the individual spectra. The atmospheric emission spectrum that is overlaid above the Orion spectrum is purely illustrative, and just shows the main features of the atmospheric emission. Recent observational and modeling studies of the terrestrial atmospheric emission (see for example Naylor et al. 2000; Pardo et al. 2001a) using collisional parameters extracted from the HITRAN database with an independent radiative transfer model (ATM) and different assumptions about line shapes produce broadly similar atmospheric emission spectra to the one shown here.

Table 1. JCMT Orion spectral line survey.

Molecule	N_{col} cm^{-3}	Error cm^{-3}	T_{rot} K	Error K	Number of lines	Note
(CH ₃) ₂ O	1.4×10^{16}	1.8×10^{15}	157	30	27(26) lines	
C ₂ H ₃ CN	3.0×10^{17}	3.2×10^{17}	180	47	13(6) lines	[1]
C ₂ H ₅ CN	2.4×10^{16}	8.4×10^{15}	150	12	27(23) lines	T_{rot} from Sut85
	8.3×10^{15}	1.2×10^{15}	239	12	27(23) lines	T_{rot} from Sch01
C ₂ H ₅ OH	5.6×10^{16}	4.0×10^{16}	70	-	8(6) lines	T_{rot} from Ohi95
	4.1×10^{16}	2.3×10^{16}	264	196	8(6) lines	
CH ₂ NH	2.4×10^{15}	5.9×10^{14}	150	-	3(2) lines	T_{rot} from HNCO
CH ₃ CN	3.6×10^{15}	4.2×10^{14}	227	21	19 lines	
CH ₃ ¹³ CN	6.0×10^{14}	2.2×10^{14}	227	-	2 lines	T_{rot} From CH ₃ CN
	2.9×10^{15}	-	74	-	2 lines	
CH ₃ OH	9.3×10^{16}	4.8×10^{16}	599	295	24(23) lines	
H ₂ CO	1.6×10^{16}	-	166	-	2(1) lines	T_{rot} from Bla87
H ₂ ¹³ CO	1.0×10^{15}	4.0×10^{14}	166	-	2 lines	T_{rot} from Bla87
HC ₃ N	1.5×10^{15}	-	164	-	2 lines	
HCOOCH ₃	5.1×10^{16}	9.5×10^{15}	301	95	26(24) lines	
HNCO	4.9×10^{15}	4.0×10^{14}	150	14	4(3) lines	
NH ₂ CN	3.3×10^{15}	8.5×10^{14}	200	-	3 lines	$T_{\text{rot}} = 200$ (K) Fix
	1.1×10^{16}	4.8×10^{15}	100	-	3 lines	$T_{\text{rot}} = 100$ (K) Fix
OCS	9.0×10^{16}	-	106	-	2 lines	
SO	3.3×10^{17}	-	72	-	2(1) lines	T_{rot} from Sut95
³⁴ SO	1.1×10^{16}	3.5×10^{15}	89	43	5(4) lines	
SO ₂	1.2×10^{17}	1.0×10^{16}	136	9	35(28) lines	
³⁴ SO ₂	8.5×10^{15}	-	156	-	3(2) lines	
¹³ CS	2.3×10^{14}	-	120	-	1 line	T_{rot} from Zen95
³⁰ SiO	3.4×10^{14}	-	50	-	1 line	T_{rot} from Sut95
CH ₃ CHO	1.1×10^{16}	-	81	-	1 line	T_{rot} from Sch97
Cl	1.2×10^{18}	-	30	-	1 line	T_{ex} from Whi95
CO	3.5×10^{18}	-	200	-	4 lines (1 transition)	T_{rot} from Sut95
DCN	1.1×10^{14}	-	200	-	1 line	T_{rot} from Bla87
HCOOH	2.2×10^{15}	-	100	-	1 line	T_{rot} from Sut95
HDO	3.2×10^{16}	-	164	-	1 line	T_{rot} from Bla87
N ₂ O	4.6×10^{16}	-	230	-	1 line	T_{rot} from Wri83
NH ₂ CHO	7.5×10^{15}	-	81	-	1 lines	T_{rot} from Sch97
NH ₂ D	8.7×10^{15}	-	160	-	1 line	T_{rot} from Her88

LTE rotation temperatures and beam averaged N_{col} , estimated using a Boltzmann plot. The N_{col} were determined using the main beam brightness temperature scale, and for species where only one line was measured, we have assumed T_{rot} as described in Col. 7. Notes: Col. 6: A(B) lines represent A: number of assigned lines, B: number of lines included in the fitting. For A lines only, all lines were included in the fitting. [1]: $v_2 = 1$ state lines were not included in the fitting, [2]: Energy levels were considered in the $v = 1$ vibrational state. Errors quoted are all 1σ .

where $\int T_{\text{mb}} dV$ is the integrated intensity of the line, S is the intrinsic strength of the transition, Q is the partition function of the molecule and μ is the dipole moment. The value of $\mu^2 S$ was calculated from the value of the transition intensity listed by Pickett et al. (1995), using Eq. (2).

$$I_{ba}(T) = \left(\frac{8\pi^3}{3hc} \right) \nu_{ba}^x S_{ba} \mu_x^2 \left[\frac{e^{\frac{E_l}{kT}} - e^{\frac{E_u}{kT}}}{Q_{rs}} \right]. \quad (2)$$

The values for T_{rot} and column densities are summarised in Table 1.

One of the objectives in analysing spectral line survey data is to determine molecular parameters, such as rotation

temperatures, column densities etc. The approach commonly adopted has been to use a “rotation diagram” to estimate these parameters. In this, an optically thin transition produces an antenna temperature that is proportional to the column density in the upper level of the transition being observed. If all transitions are thermalised and the kinetic temperature is known, then a single integrated line intensity can be used to estimate the total column density of the species in question. The rotational temperature diagram is a plot showing the column density per statistical weight of a number of molecular energy levels, as a function of energy above the ground state – in local thermodynamic equilibrium (LTE), this is equivalent to a Boltzmann

distribution. A plot of the natural logarithm of the column density, N , divided by the degeneracy g , versus the Energy E of the final state of the level (expressed in units of degrees K) E/k , will lead to a straight line fit with a slope of $1/T$, where g is the statistical weight of level u lying at E energy above the ground state, and T is the rotational temperature. This is equivalent to the kinetic temperature in the limit where all of the levels are thermalised.

One problem for the rotation diagram method is that it may underestimate the total column density if some of the lines fitted are optically thick, or LTE conditions do not hold, or if the background radiation is non-negligible (Turner 1991; Goldsmith & Langer 1999; Nummelin et al. 2000; Schilke et al. 2001). This can however be addressed by using less abundant isotopomeric variants that allow estimates to be made of the optical depths, and then using these to correct the column density estimates. It has however been widely used in past molecular line survey studies, because of its computational simplicity, and the absence of a need to have observations of an isotopomer. In this paper we give results from the traditional rotation-diagram technique (Table 1), except in cases pointed out in the Table and text where the results may be affected by high optical depth effects. We have examined a number of cases (CH_3CN , SO_2 , OCS , SO , CH_3OH and ^{34}SO in some detail – see for example Sects. 4.3 and 4.2 – calculating the optically thick and thin total column densities – and found the use of the rotational temperature technique to provide similar column density estimates are quite similar to the rotational diagram values (see for example discussion of opacities in Sect. 4.2). Another indicator as to whether opacity corrections are important, is to look at the rotational temperature diagrams (see Fig. 7), to see whether there are data points that deviate noticeably from a straight line fit – and which may indicate that the line has saturated. Lee et al. (2001) applied this kind of constraint to seven molecules (CH_3OH , HCOOCH_3 , CH_3OCH_3 , $\text{C}_2\text{H}_5\text{CN}$, SO_2 , CH_3CN , and H_2CO), finding that the majority could to first order be treated using the rotational technique. The issue of opacity will be further discussed in the relevant sections dealing with molecules that may be opaque – where we also conclude that the effects of opacity are minor in the analysis of data from this survey, and that our justification of using the optically thin rotational temperature technique is adequate although there are clear examples (Schilke et al. 1997, 2001) where opacity corrections are required for CH_3OH .

Full details of the detected lines are given in Tables 2–6.

4. Discussion of individual species

Individual spectra are shown in more detail in Figs. 3, 4, 5 and 6, along with identifications of the prominent lines. Previous studies (Blake et al. 1987; Schilke et al. 1997, 2001) have shown that there are four characteristic velocity components in Orion spectra: the extended ridge – which is ambient gas in the Orion Molecular cloud ($v_{\text{lsr}} \sim 9 \text{ km s}^{-1}$ $\Delta v \sim 4 \text{ km s}^{-1}$), the compact ridge – which is a compact clump lying about $10''$ south-west of the hot core ($v_{\text{lsr}} \sim 8 \text{ km s}^{-1}$ $\Delta v \sim 3 \text{ km s}^{-1}$), the plateau – which has been identified as the outflow, and is associated with the broadest spectral lines

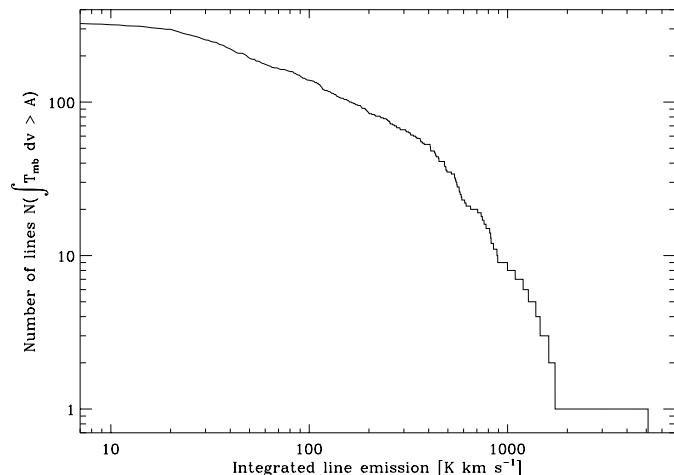


Fig. 2. Cumulative spectrum showing the number of lines detected that exceeded some value.

($v_{\text{lsr}} \sim 6\text{--}10 \text{ km s}^{-1}$ $\Delta v \sim 20 \text{ km s}^{-1}$), and the hot core that lies close to the infrared source IRC2 ($v_{\text{lsr}} \sim 3\text{--}6 \text{ km s}^{-1}$ $\Delta v \sim 5\text{--}10 \text{ km s}^{-1}$). Most of the observed lines show velocities within these ranges, except a few lines which may suffer from blending (e.g. lines at 455.7798, 459.7069, 466.7817, 495.0007, 496.44095, 503.8517, 504.7281 GHz). The superposed dotted line shows the normalised atmospheric absorption (see Fig. 1 caption) under conditions typical for the survey.

4.1. CO

In this survey the CO $J = 4\text{--}3$ transition is the most intense single line, with a full width at half maximum of 40 km s^{-1} and full width at zero intensity of at least 120 km s^{-1} . The peak main beam brightness temperature $T_{\text{mb}} = 182 \text{ K}$ was similar to values that we have previously measured using the JCMT (see for example White & Sandell 1995). The line profile clearly shows a small dip close to its peak, which is probably a self-absorption dip. This has also been reported by Schilke et al. (2001) in the $J = 6\text{--}5$ transition, and was seen in all of our earlier unpublished JCMT spectra in this transition using both the present SIS receiver, as well as the original JCMT 460–490 GHz Indium Antimonide receiver (White & Padman 1991; Padman & White 1992). We have made careful checks on the many occasions that we have observed this line with the JCMT, confirming that this dip is not a result of the subtraction of emission located at the off position. Unpublished maps (in preparation) of the spatial distribution of this absorption feature show it to be spatially localised on the hot core, and that larger scale CO emission is spatially extended around the core – meaning that the T_{mb} may overestimate the true kinetic temperature.

4.2. Sulphur monoxide (SO) and sulphur dioxide (SO_2)

The high abundances of sulphur based molecules in the interstellar medium are believed to be in part due to the presence of shocks, that favour the endothermic reactions required to

Table 2. JCMT Orion spectral linesurvey.

Frequency MHz	Species	Transition	Peak T_{mb} K	Width km s ⁻¹	Vel km s ⁻¹	Notes
455.160796	SO ₂	21 _{5,17} -21 _{4,18}	23.2	33.3	8.2	
455.250265	SO ₂	29 _{5,25} -29 _{4,26}	14.8	19.6	6.9	
455.353721	SO ₂	18 _{5,13} -18 _{4,14}	17.6	8.0	5.4	
455.450207	U-line		4.3	9.4		
455.617930	CH ₃ OH	6 ₁ -5 ₀	36.1	10.6	9.1	
455.779855	SO ₂	11 _{3,9} -10 _{2,8}	60.2	13.8	1.6	Blend with C ₂ H ₃ CN
456.271440	CH ₃ OH	18 ₁ -17 ₂	20.2	6.2	8.4	
456.359253	SO ₂	19 _{5,15} -19 _{4,16}	29.5	11.6	4.4	
456.513228	U-line		18.8	4.3		
456.553270	U-line		4.7	16.6		C ₃ H ₂ 22 _{0,22} -21 _{0,21} ?
456.800826	CH ₃ OH	18 ₋₂ -18 ₋₁	12.7	7.9	5.3	Blend with C ₂ H ₅ CN
456.936702	(CH ₃) ₂ O	15 _{3,12} -14 _{2,13}	5.0	9.3	6.9	4 lines blended
457.006904	CH ₃ OH	11 ₂ -11 ₁	23.7	7.6	8.2	
457.248931	CH ₃ OH	19 ₋₁ -18 ₋₂	9.3	15.6	9.9	
457.325926	SO ₂	16 _{5,11} -16 _{4,12}	30.4	11.3	2.2	Blend with C ₂ H ₃ CN
457.381156	SO ₂	15 _{8,8} -16 _{7,9} +15 _{8,7} -16 _{7,10}	7.5	14.6	7.8	
457.472642	SO ₂	17 _{5,13} -17 _{4,14}	50.1	11.4	5.2	
457.584559	U-line		7.0	3.5		
457.637840	U-line		3.5	7.3		
457.723839	C ₂ H ₅ CN	51 _{8,44} -50 _{8,43}	5.1	5.2	11.5	
457.736126	HCOOCH ₃	40 _{3,37} -39 _{3,36}	9.2	6.0	7.4	
457.783725	U-line		13.3	9.4		
457.822031	U-line		9.1	28.5		
457.839618	U-line		4.7	4.3		SO ₂ $v_2 = 1$?
457.878236	C ₂ H ₅ CN	53 _{2,52} -52 _{2,51}	5.4	4.3	5.2	
457.890562	C ₂ H ₅ CN	28 _{5,23} -27 _{4,24}	5.9	6.0	9.3	
457.947140	HCOOCH ₃	38 _{6,32} -37 _{5,32}	3.4	6.0	10.5	
457.985674	HCOOH	20 _{3,17} -19 _{3,16}	3.8	2.8	9.6	
458.022659	C ₂ H ₅ CN	48 _{4,45} -47 _{3,44}	4.9	10.3	7.2	
458.148139	CH ₃ OH	10 ₁ -9 ₂	15.3	7.0	7.0	
458.276916	(CH ₃) ₂ O	25 _{1,24} -24 _{2,23}	11.6	3.9	8.8	4 lines blended
458.389953	SO ₂	15 _{5,11} -15 _{4,12}	40.8	25.2	6.9	
458.433457	C ₂ H ₅ OH	28 _{1,28} -27 _{1,27}	8.2	5.3	6.1	
458.512326	HCOOCH ₃	41 _{2/3/2/2,39} -40 _{3/3/2/2,38}	20.7	12.2	8.5	4 lines blended
458.536360	SO ₂	14 _{5,9} -14 _{4,10}	34.8	16.7	5.9	
458.601426	HCOOCH ₃	36 _{11,25} -35 _{11,24}	7.1	8.0	9.9	
458.619675	SO ₂	31 _{5,27} -31 _{4,28}	8.6	9.8	3.8	
458.998198	CH ₃ CN	$J = 25-24$ $K = 9$	3.9	5.7	7.3	
459.054419	U-line		20.5	22.1		
459.076694	SO ₂	13 _{5,9} -13 _{4,10}	36.0	14.1	5.0	
459.150830	CH ₃ CN	$J = 25-24$ $K = 8$	4.3	11.2	4.9	
459.257959	U-line		23.3	24.2		
459.378018	U-line		8.3	6.1		
459.395715	CH ₃ CN	$J = 25-24$ $K = 6$	17.7	10.4	5.4	Blend with CH ₃ ¹³ CN $J = 25-24$ $K = 3$
459.443401	CH ₃ ¹³ CN	$J = 25-24$ $K = 2$	4.7	13.9	9.6	
459.492742	CH ₃ CN	$J = 25-24$ $K = 5$	20.4	16.7	5.3	Blend with CH ₃ ¹³ CN $J = 25-24$ $K = 0,1$
459.511802	NH ₂ CN	23 _{4,20/19} -22 _{4,19/18}	16.0	9.3	9.0	
459.534263	SO ₂	11 _{5,7} -11 _{4,8}	39.4	19.7	5.2	
459.569872	CH ₃ CN	$J = 25-24$ $K = 4$	17.3	13.6	6.6	
459.631405	CH ₃ CN	$J = 25-24$ $K = 3$	30.9	13.0	6.6	
459.678274	CH ₃ CN	$J = 25-24$ $K = 2$	37.8	10.8	4.8	
459.706888	CH ₃ CN	$J = 25-24$ $K = 0,1$	35.4	15.5	3.3	2 lines blended
459.760261	HNCO	21 _{1,21} -20 _{1,20}	14.8	7.2	6.1	
459.801217	SO ₂	9 _{5,4} -9 _{4,5} +9 _{5,5} -9 _{4,6}	35.0	22.8	8.1	
459.881164	SO ₂	8 _{5,3} -8 _{4,4} +8 _{5,4} -8 _{4,5}	49.9	32.7	7.6	
459.942528	SO ₂	7 _{5,3} -7 _{4,4}	57.9	26.2	4.8	
459.983548	SO ₂	5 _{5,0} -5 _{4,1} +5 _{5,1} -5 _{4,2}	53.6	25.6	11.4	

Table 3. JCMT Orion spectral linesurvey.

Frequency MHz	Species	Transition	Peak T_{mb} K	Width km s ⁻¹	Vel km s ⁻¹	Notes
460.069658	C ₂ H ₅ CN	31 _{4,27} -30 _{3,28}	2.6	23.5	7.3	
460.214973	HCOOCH ₃	37 _{6,31} -36 _{6,30}	6.5	3.6	8.8	
460.272941	³⁴ SO ₂	6 _{4,2} -5 _{3,3}	7.5	31.1	7.8	
460.281266	HCOOCH ₃	43 _{1,43} -42 _{1,42}	8.8	6.9	9.6	
460.306531	C ₂ H ₅ CN	22 _{15,7/8} -23 _{14,10/9}	4.0	2.3	7.1	
460.387575	HCOOCH ₃	37 _{12,26} -36 _{12,25}	3.1	27.3	8.0	2 lines blended
460.466108	U-line		3.0	13.7		
460.545686	U-line		6.2	6.2		
460.591671	U-line		5.0	3.9		
460.878573	CH ₃ OH	9 ₂ -8 ₁	24.4	6.6	7.3	
460.913504	U-line		3.8	5.0		
461.040768	CO	$J = 4-3$	182.0	51.0	9.0	
461.342825	U-line		5.0	7.5		
461.373909	HNCO	21 _{2,19} -20 _{2,18}	7.4	6.1	5.7	
461.709888	HCOOCH ₃	30 _{7,24} -29 _{6,23}	5.5	8.4	9.6	
461.756285	CH ₃ OH	15 ₀ -14 ₁	43.8	11.8	7.8	
461.880198	SO ₂	20 _{9,11} -21 _{8,14} +20 _{9,12} -21 _{8,13}	7.9	12.6	6.2	
461.910483	OCS	$J = 38-37$	18.1	11.8	7.2	
462.035190	CH ₃ OH $v_t = 1$	10 ₆ -11 ₅ +	8.1	13.0	9.8	
462.036358	C ₂ H ₅ OH	13 _{5,9} -12 _{4,8}	8.1	13.0	12.5	Blended with CH ₃ CN
462.138660	HCOOCH ₃	37 _{11,27} -36 _{11,26}	3.5	7.0	8.4	
462.236037	³⁴ SO		42.0	19.3		
462.334032	¹³ CS	$J = 10-9$	14.6	16.4	6.8	Blended with C ₂ H ₅ CN
463.017334	SO ₂	12 _{2,10} -11 _{1,11}	21.3	23.0	5.2	
463.122260	HNCO	21 _{1,20} -20 _{1,19}	8.5	6.8	7.2	
463.329490	SO ₂	35 _{4,32} -35 _{3,33}	5.6	14.3	6.9	
463.720861	HC ₃ N	$J = 51-50$	8.2	13.2	5.4	
463.836119	³⁴ SO ₂	26 _{0,26} -25 _{1,25}	8.2	10.4	9.1	
464.026804	U-line		6.8	25.2		
464.091929	³⁴ SO	$N_J = 11_{11}-10_{10}$	20.8	25.8	11.6	
464.200231	CH ₃ CHO	7 _{4,4} -6 _{3,3}	4.2	5.8	7.9	Blend with HCOOCH ₃
464.200231	HCOOCH ₃	37 _{10,28} -36 _{10,27}	4.2	5.8	9.5	Blend with CH ₃ CHO
464.293855	SO ₂	33 _{5,29} -33 _{4,30}	4.1	10.8	5.1	
464.570359	CH ₂ NH	7 _{1,6} -6 _{1,5}	4.4	16.8	8.5	
464.730426	U-line		12.9	6.6		
464.837513	CH ₃ OH	9 ₂ -9 ₁	34.0	11.3	7.2	Blend with C ₂ H ₅ CN 9 ₂ -9 ₁
464.928173	HDO	1 _{0,1} -0 _{0,0}	33.5	16.2	6.6	
465.061222	C ₂ H ₃ CN	52 _{2,49} -49 _{2,48} $v_2 = 1$	1.9	11.1	12.3	
465.078910	U-line		3.6	4.1		
465.352350	³⁴ SO	$N_J = 11_{12}-10_{11}$	30.5	23.0	7.2	
465.512820	U-line		2.4	5.4		
465.543972	(CH ₃) ₂ O	21 _{3,19} -20 _{2,18}	3.6	11.2	5.9	4 lines blended
465.565977	HCOOCH ₃	36 _{1,35} -35 _{1,34}	2.4	14.7	9.0	
465.605514	C ₂ H ₅ CN	52 _{12,41/40} -51 _{12,40/39}	4.0	11.2	4.4	
465.628191	SO ₂	29 _{2,28} -29 _{1,29}	13.0	8.4	5.1	
465.713762	C ₂ H ₅ CN	51 _{5,46} -50 _{5,45}	7.4	13.2	5.9	
465.732611	NH ₂ CHO	22 _{1,21} -21 _{1,20}	16.1	9.7	6.7	
465.758340	SO ₂	26 _{0,26} -25 _{1,25}	45.3	15.8	4.4	
465.882288	(CH ₃) ₂ O	14 _{4,11} -13 _{3,10}	4.0	9.9	6.1	Blend with SO ₂
465.882288	SO ₂	25 _{10,16} -26 _{9,17} +25 _{10,15} -26 _{9,18}	4.0	9.9	8.7	Blended with (CH ₃) ₂ O
465.922779	SO ₂ $v_2 = 1$	18 _{5,13} -18 _{4,14}	2.2	9.5	7.9	
465.956339	³⁰ SiO	$J = 11-10$	7.7	15.1	8.8	
466.781659	C ₂ H ₃ CN	49 _{13,36/37} -48 _{13,35/36} $v_1 = 1$	13.8	30.7	11.9	Blended with C ₂ H ₅ CN
466.781659	C ₂ H ₃ CN	52 _{8,44} -51 _{8,43}	13.8	30.7	3.8	Blend with C ₂ H ₃ CN
466.892775	SO ₂	40 _{6,34} -40 _{5,35}	5.5	5.5	5.7	
466.999547	U-line		3.1	5.6		
467.048535	HCOOCH ₃	38 _{23,16/15} -37 _{23,15/14}	5.6	14.7	8.9	

Table 4. JCMT Orion spectral linesurvey.

Frequency MHz	Species	Transition	Peak T_{mb} K	Width km s ⁻¹	Vel km s ⁻¹	Notes
467.212513	HCOOCH ₃	38 _{22,17} -37 _{22,16}	4.6	5.5	8.6	
467.282605	C ₂ H ₃ CN	49 _{16,33/34} -48 _{16,32/33} $v_1 = 1$	6.9	7.6	8.2	
467.318607	HCOOCH ₃	39 _{6,34} -38 _{6,33}	3.9	19.2	9.4	2 lines blended
467.475284	U-line		10.5	8.3		
467.532613	(CH ₃) ₂ O	26 _{0,26} -25 _{1,25}	6.2	5.4	7.7	4 lines blended
467.586402	HCOOCH ₃	39 _{5,34} -38 _{5,33}	3.7	10.5	8.3	
467.627790	HCOOCH ₃	19 _{9,10} -18 _{8,10}	2.8	10.2	8.5	
467.658900	U-line		6.0	17.2		
467.670464	C ₂ H ₅ OH	15 _{3,12} -14 _{2,12}	10.4	6.4	9.4	
467.715623	(CH ₃) ₂ O	26 _{1,26} -25 _{1,25}	14.4	13.0	5.6	4 lines blended
467.765733	¹³ CH ₃ OH	10 ₁ -9 ₁ $v_t = 0,1$	7.1	6.4		
468.048223	C ₂ H ₅ CN	55 _{0,55} -54 _{0,54}	2.9	12.8	6.5	
468.300479	CH ₃ OH	8 ₂ -8 ₁	20.3	8.4	4.7	Blend with U-line
468.345184	U-line		7.6	6.0		
491.943519	SO ₂	7 _{4,4} -6 _{3,3}	49.4	10.3	3.6	
491.978910	H ₂ CO	7 _{1,7} -6 _{1,6}	45.0	13.6	2.6	
492.160626	Cl	³ P ₁ - ³ P ₁	17.9	5.0	9.0	
492.281601	CH ₃ OH	4 ₁ -3 ₀	36.9	10.4	7.2	
492.470010	U-line		5.2	8.5		
492.544658	C ₂ H ₅ CN	55 _{11,45/44} -54 _{11,44/43}	3.5	4.3	5.3	
492.695825	¹³ CH ₃ OH		9.9	4.7	8.1	
492.784191	(CH ₃) ₂ O	9 _{6,4} -8 _{5,4}	20.7	8.4	8.6	8 lines blended
493.260821	C ₂ H ₅ CN	58 _{1/0,58} -57 _{1/0,57}	4.4	7.4	6.2	
493.370372	U-line		9.6	11.4		
493.701318	CH ₃ OH	5 ₃ -4 ₂	23.7	11.4	7.6	
493.735068	CH ₃ OH	5 ₃ -4 ₂	29.0	9.3	8.1	
494.460056	NH ₂ D	1 _{1,0} - 0 _{0,0}	10.5	8.6	5.8	
494.484560	CH ₃ OH	7 ₂ -7 ₁	50.8	10.3	7.2	
494.555486	SO ₂	13 ₂ 7-12 ₂ 8	2.5	4.2	7.6	
494.557464	C ₂ H ₅ CN	55 _{7,49} -54 _{7,48}	2.5	4.2	5.4	Blend with C ₂ H ₅ OH
494.557464	C ₂ H ₅ OH	10 _{9,1} -9 _{8,1}	2.5	4.2	8.7	Blend with C ₂ H ₅ CN
494.575046	C ₂ H ₅ CN	32 _{5,27} -31 _{4,28}	2.6	6.4	9.5	
494.596465	(CH ₃) ₂ O	28 _{9,19} -28 _{8,20} +28 _{9,20} -28 _{8,21}	5.7	5.3	7.7	8 lines blended
494.756403	C ₂ H ₃ CN	52 _{17,35/36} -51 _{17,34/35} $v = 0$	14.1	17.1	5.2	
494.781464	SO ₂	12 _{3,9} -11 _{2,10}	45.0	26.6	7.9	
494.899521	C ₂ H ₅ OH	28 _{3,25} -27 _{3,24}	1.8	10.5	3.1	
495.000693	(CH ₃) ₂ O	27 _{9,18} -27 _{8,19} +27 _{9,19} -27 _{8,20}	1.6	15.1	10.9	8 lines blended
495.222806	(CH ₃) ₂ O	27 _{1,26} -26 _{2,25}	7.8	14.4	7.5	4 lines blended
495.486885	HCOOCH ₃	39 _{7,32} -38 _{7,31}	12.5	4.8	7.4	
495.821871	C ₂ H ₅ OH	26 _{4,22} -25 _{3,22}	2.1	2.8	3.5	
495.842389	SO ₂	13 _{8,6} -14 _{7,7} +13 _{8,5} -14 _{7,8}	9.8	20.5	8.5	
495.979430	(CH ₃) ₂ O	24 _{9,15} -24 _{8,16} +24 _{9,16} -24 _{8,17}	8.7	5.8	7.1	8 lines blended with CH ₃ CN
495.979430	CH ₃ CN	$J = 27-26$ $K = 7$	8.7	5.8	7.0	Blend with (CH ₃) ₂ O
496.107704	CH ₃ CN	$J = 27-26$ $K = 6$	11.5	11.6	4.6	
496.207453	CH ₃ CN	$J = 27-26$ $K = 5$	8.8	13.3	6.6	
496.295793	CH ₃ CN	$J = 27-26$ $K = 4$	13.3	11.1	4.8	
496.361787	CH ₃ CN	$J = 27-26$ $K = 3$	19.2	11.6	5.1	
496.409463	CH ₃ CN	$J = 27-26$ $K = 2$	20.7	12.5	5.0	
496.440950	(CH ₃) ₂ O	24 _{9,15} -24 _{8,16} +24 _{9,16} -24 _{8,17}	26.6	17.0	10.9	8 lines blended with CH ₃ CN
495.175350	CH ₃ OH	7 ₀ -6 ₋₁	39.7	10.2	7.7	
496.440950	CH ₃ CN	$J = 27-26$ $K = 1$	26.6	17.0	3.2	2 lines blended, Blend with (CH ₃) ₂ O
496.518825	H ₂ ¹³ CO	7 _{2,6} -6 _{2,5}	3.1	7.2	6.3	
496.633861	(CH ₃) ₂ O	21 _{9,12} -21 _{8,13} +21 _{9,13} -21 _{8,14}	7.0	5.2	8.4	8 lines blended
496.764492	C ₂ H ₃ CN	52 _{5,47} -51 _{5,46} $v_2 = 1$	2.2	14.4	14.1	
496.796267	(CH ₃) ₂ O	20 _{9,11} -20 _{8,12} +20 _{9,12} -20 _{8,13}	5.8	3.8	8.4	8 lines blended
496.928524	CH ₃ OH	14 ₀ -13 ₁	16.7	9.2	6.5	
497.051216	(CH ₃) ₂ O	18 _{9,9} -18 _{8,10} +18 _{9,10} -18 _{8,11}	7.2	14.8	8.6	8 lines blended

Table 5. JCMT Orion spectral linesurvey.

Frequency MHz	Species	Transition	Peak T_{mb} K	Width km s ⁻¹	Vel km s ⁻¹	Notes
497.085708	C ₂ H ₅ OH	9 _{7,3/2} -8 _{6,2/3}	3.1	10.4	10.3	
497.119025	H ₂ ¹³ CO	7 _{4,4/3} -6 _{4,3/2}	4.8	6.9	6.6	
497.149132	(CH ₃) ₂ O	17 _{9,8} -17 _{8,9} +17 _{9,9} -17 _{8,10}	6.4	7.3	8.5	8 lines blended
497.226494	(CH ₃) ₂ O	16 _{9,7} -16 _{8,8} +16 _{9,8} -16 _{8,9}	5.5	4.8	10.4	8 lines blended
497.295820	(CH ₃) ₂ O	15 _{9,6} -15 _{8,7} +15 _{9,7} -15 _{8,8}	5.2	3.2	8.1	4 lines blended
497.364091	U-line		3.7	7.0		
497.388286	(CH ₃) ₂ O	13 _{9,4} -13 _{8,5} +13 _{9,5} -13 _{8,6}	8.5	10.8	8.4	8 lines blended
497.404849	U-line		4.4	1.5		
497.417697	(CH ₃) ₂ O	12 _{9,3} -12 _{8,4} +12 _{9,4} -12 _{8,5}	9.4	8.4	9.4	8 lines blended
497.442262	(CH ₃) ₂ O	11 _{9,2} -11 _{8,3} +11 _{9,3} -11 _{8,4}	4.2	9.4	8.3	8 lines blended with HCOOCH ₃
497.442262	HCOOCH ₃	40 _{13,28} -39 _{13,27} +40 _{15,26} -39 _{13,27}	4.2	9.4	9.0	2 lines blended with (CH ₃) ₂ O
497.516476	C ₂ H ₃ CN	60 _{1,59} -60 _{1,60} $v = 0$	4.8	6.1	6.8	
497.556527	U-line		1.5	9.4		
497.606988	(CH ₃) ₂ O	24 _{3,22} -23 _{2,21}	4.3	2.7	8.5	4 lines blended
497.661575	C ₂ H ₅ CN	56 _{3,53} -55 _{3,52}	4.9	6.0	3.5	Blend with CH ₃ CN $v = 8$
497.661575	CH ₃ CN $v_8 = 1$	$J = 27-26$ $K = 4$ $-l$	4.9	6.0	4.9	Blend with C ₂ H ₅ CN
497.734975	CH ₃ CN $v_8 = 1$	$J = 27-26$ $K = 3$ $-l$	3.5	4.5	8.8	
497.828685	CH ₃ OH	8 ₂ -8 ₁ -	14.0	9.4	8.7	
497.905738	CH ₃ CN $v_8 = 1$	$J = 27-26$ $K = 4$ $+l$	3.6	6.4	5.9	
498.288253	C ₂ H ₅ CN	57 _{2,55} -56 _{2,54}	2.2	6.6	5.1	
498.327509	OCS	$J = 41-40$	12.6	10.2	6.6	
498.412959	CH ₃ CN $v_8 = 1$	$J = 27-26$ $K = 1$ $+l$	6.4	6.8	6.9	
498.431868	³⁴ SO ₂	8 _{4,4} -7 _{3,5}	5.9	12.2	10.0	
498.596075	HCOOCH ₃	41 _{7,35} -40 _{7,34}	2.2	8.1	9.2	
498.677131	¹³ CH ₃ OH	8 ₂ -8 ₁	8.5	7.3	4.8	
498.785157	C ₂ H ₅ CN	55 _{4,51} -54 _{4,50}	2.0	9.8	4.5	
498.849325	(CH ₃) ₂ O	16 _{4,13} -15 _{3,12}	7.7	7.0	8.5	4 lines blended with HCOOCH ₃
498.849325	HCOOCH ₃	42 _{5,37} -41 _{5,36}	7.7	7.0	6.8	Blend with (CH ₃) ₂ O
498.984855	C ₂ H ₅ CN	55 _{6,49} -54 _{6,48}	5.4	23.7	12.0	
499.198900	HCOOCH ₃	43 _{5,39} -42 _{5,38}	3.0	6.5	8.1	
499.283980	C ₂ H ₃ CN	20 _{4,17} -19 _{3,16} $v_1 = 1$	3.4	13.9	7.3	Blend with C ₂ H ₅ CN
499.283980	C ₂ H ₅ CN	17 _{8,10/9} -16 _{7,9/10}	3.4	13.9	3.4	Blend with C ₂ H ₃ CN
499.367702	(CH ₃) ₂ O	27 _{2,26} -26 _{1,25}	3.9	6.1	7.1	4 lines blended
499.892902	C ₂ H ₅ CN	58 _{1,2,57} -57 _{1,2,56}	9.1	8.0	5.4	
499.917085	NH ₂ CN	25 _{2,23} -24 _{2,22}	8.1	8.1	8.2	¹³ C ³⁴ S $J = 11-10$?
499.944145	U-line		10.2	9.6		
500.038140	HC ₃ N	$J = 55-54$	9.0	7.9	6.8	
500.052075	NH ₂ CN	25 _{3,22} -24 _{3,21}	8.0	11.8	4.9	
500.075688	SO ₂ $v_2 = 1$	7 _{4,4} -6 _{3,3}	3.8	11.5	8.6	
500.364813	C ₂ H ₃ CN	41 _{6,35} -41 _{5,36} $v_2 = 1$	4.9	5.7	6.8	
500.432652	SO ₂	18 _{9,9} -19 _{8,12} +18 _{9,10} -19 _{8,11}	20.1	6.0	8.3	
500.457324	C ₂ H ₅ CN	12 _{9,3/4} -11 _{8,4/3}	22.3	8.2	2.9	
500.475691	CH ₂ NH	2 _{2,1} -2 _{1,2}	18.0	7.5	6.3	
500.637890	C ₂ H ₅ CN	35 _{5,31} -34 _{4,30}	5.9	5.1	5.5	
500.661562	SO ₂	31 _{2,30} -31 _{1,31}	9.0	13.3	5.3	
501.087663	C ₂ H ₃ CN	55 _{1,55} -54 _{1,54} $v_1 = 1$	11.7	12.8	10.4	
501.116812	SO ₂	28 _{0,28} -27 _{1,27}	21.5	19.1	3.5	
501.592173	CH ₃ OH	9 ₂ -9 ₁ -	32.9	11.7	7.1	
501.656920	C ₂ H ₅ CN	59 _{1,0,59} -58 _{1,0,58}	5.6	8.1	8.2	
501.679997	CH ₂ NH	8 _{0,8} -7 _{0,7}	4.4	11.5	9.0	
501.891221	(CH ₃) ₂ O	30 _{3,27} -29 _{4,26}	2.8	12.0	9.1	4 lines blended
502.181627	HCOOCH ₃	15 _{12,3/4} -14 _{11,4/3}	4.6	7.0	8.2	
502.303684	N ₂ O	$J = 20-19$	3.4	17.4	4.7	
503.018652	(CH ₃) ₂ O	28 _{0,28} -27 _{1,27}	10.4	10.7	7.4	4 lines blended
503.107069	(CH ₃) ₂ O	28 _{1,28} -27 _{0,27}	5.1	5.2	9.2	4 lines blended
503.210868	HCOOCH ₃	40 _{8,32} -39 _{8,31}	2.7	7.6	8.5	
503.518307	HCOOCH ₃	22 _{9,13} -21 _{8,14}	6.2	6.1	7.6	

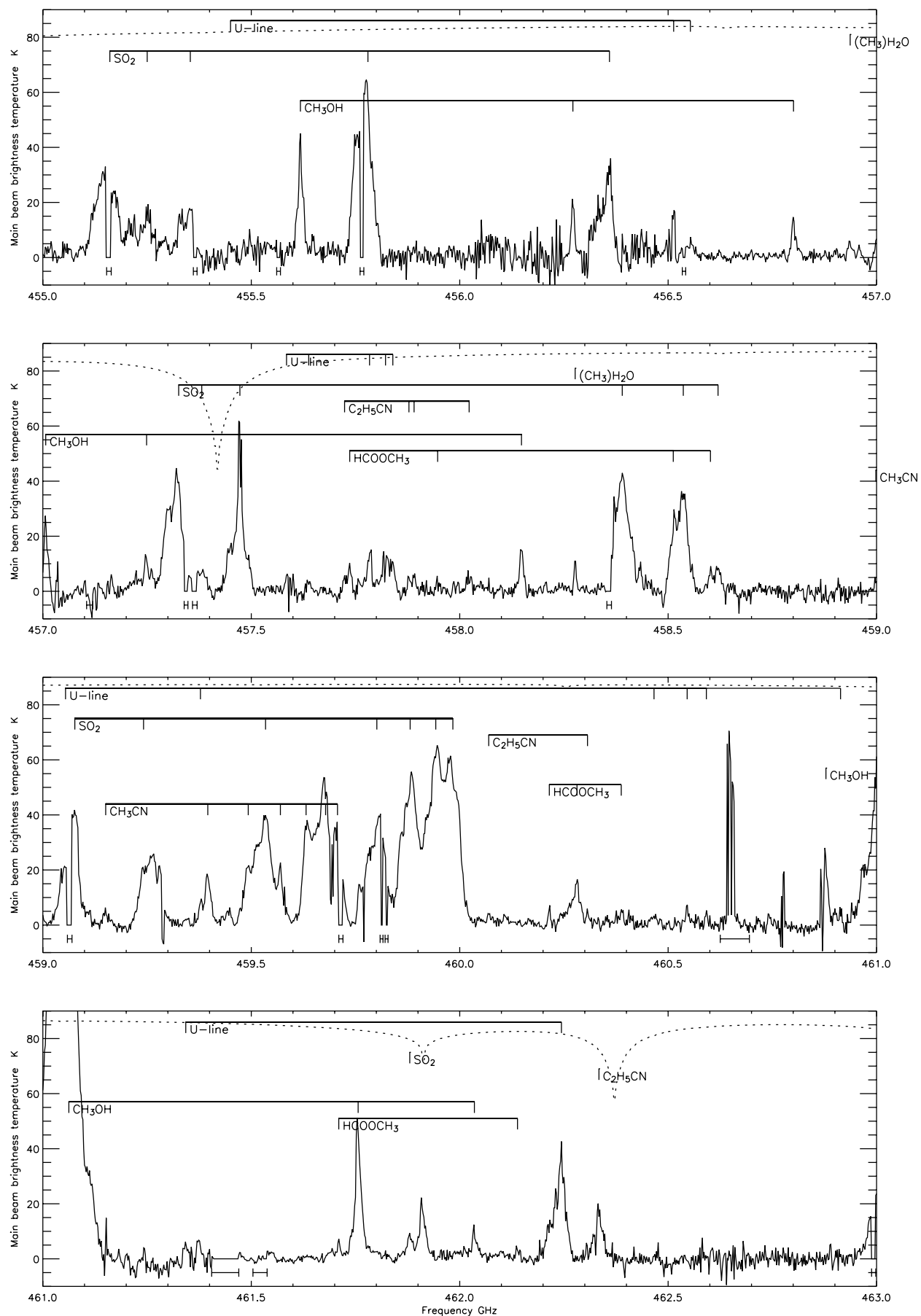


Fig. 3. Spectra and lines detected in the survey. The locations of parts of the spectra that were poorly deconvolved are indicated by horizontal lines placed underneath the spectrum.

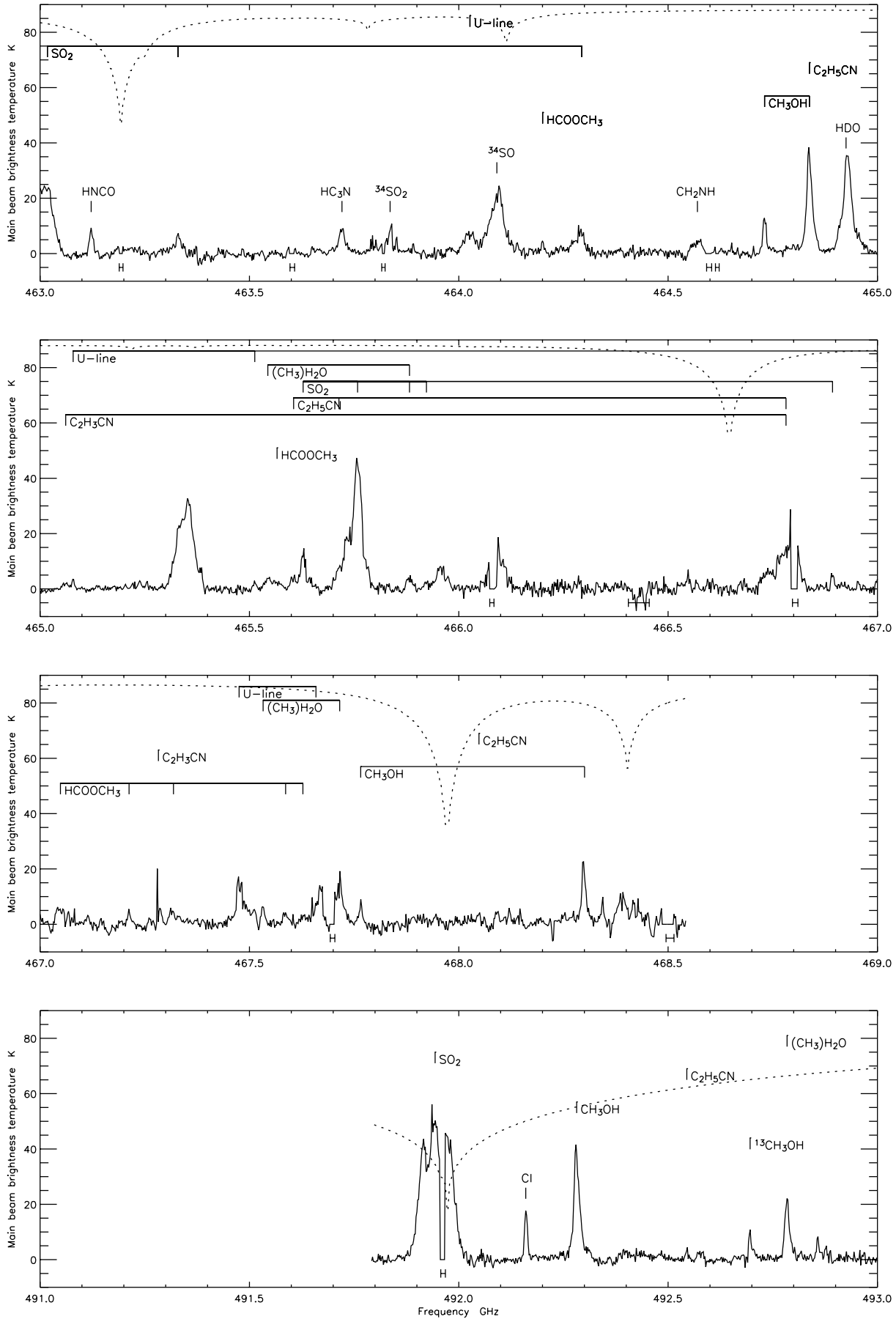


Fig. 4. Spectra and lines detected in the survey. The locations of parts of the spectra that were poorly deconvolved are indicated by horizontal lines placed underneath the spectrum.

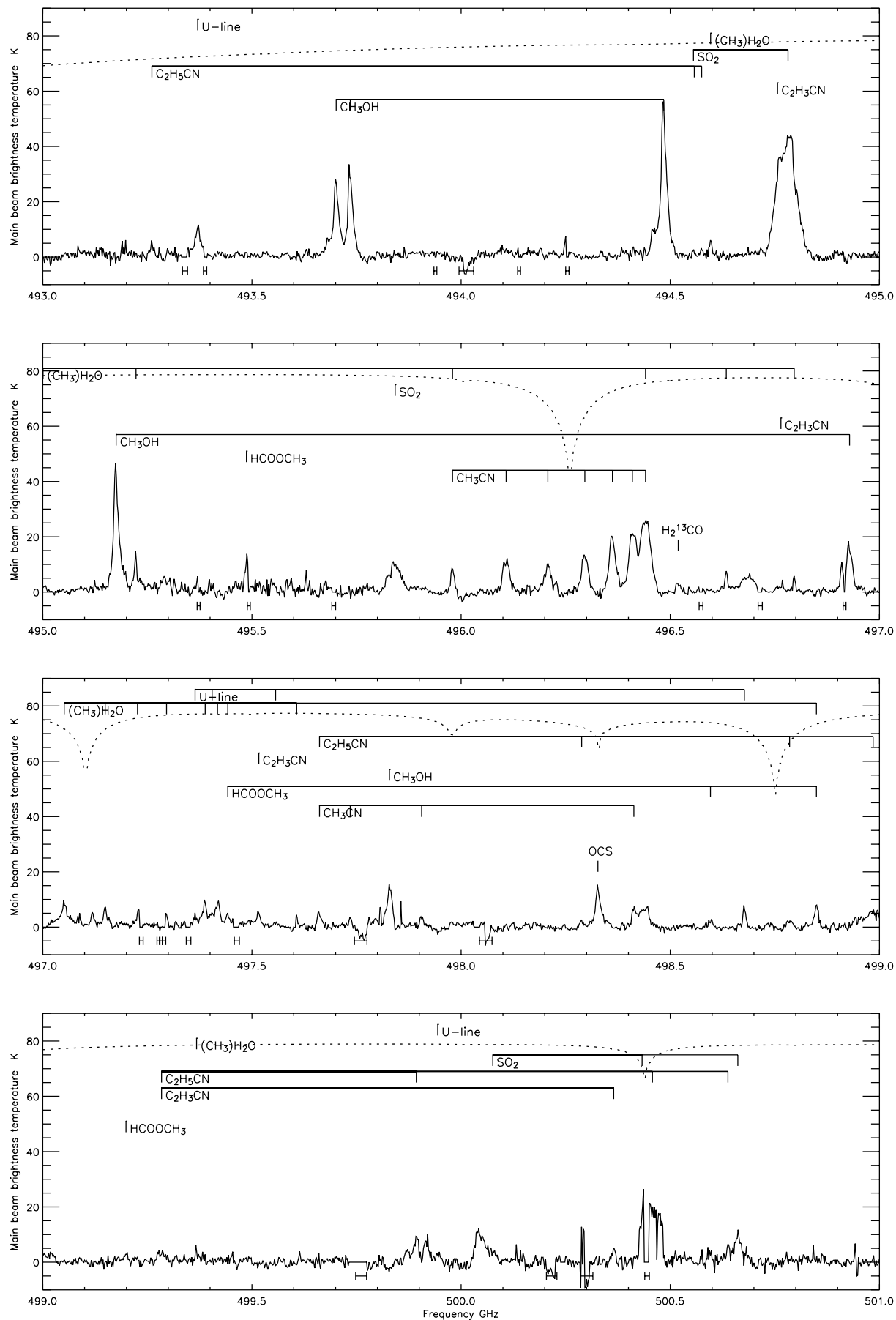


Fig. 5. Spectra and lines detected in the survey. The locations of parts of the spectra that were poorly deconvolved are indicated by horizontal lines placed underneath the spectrum.

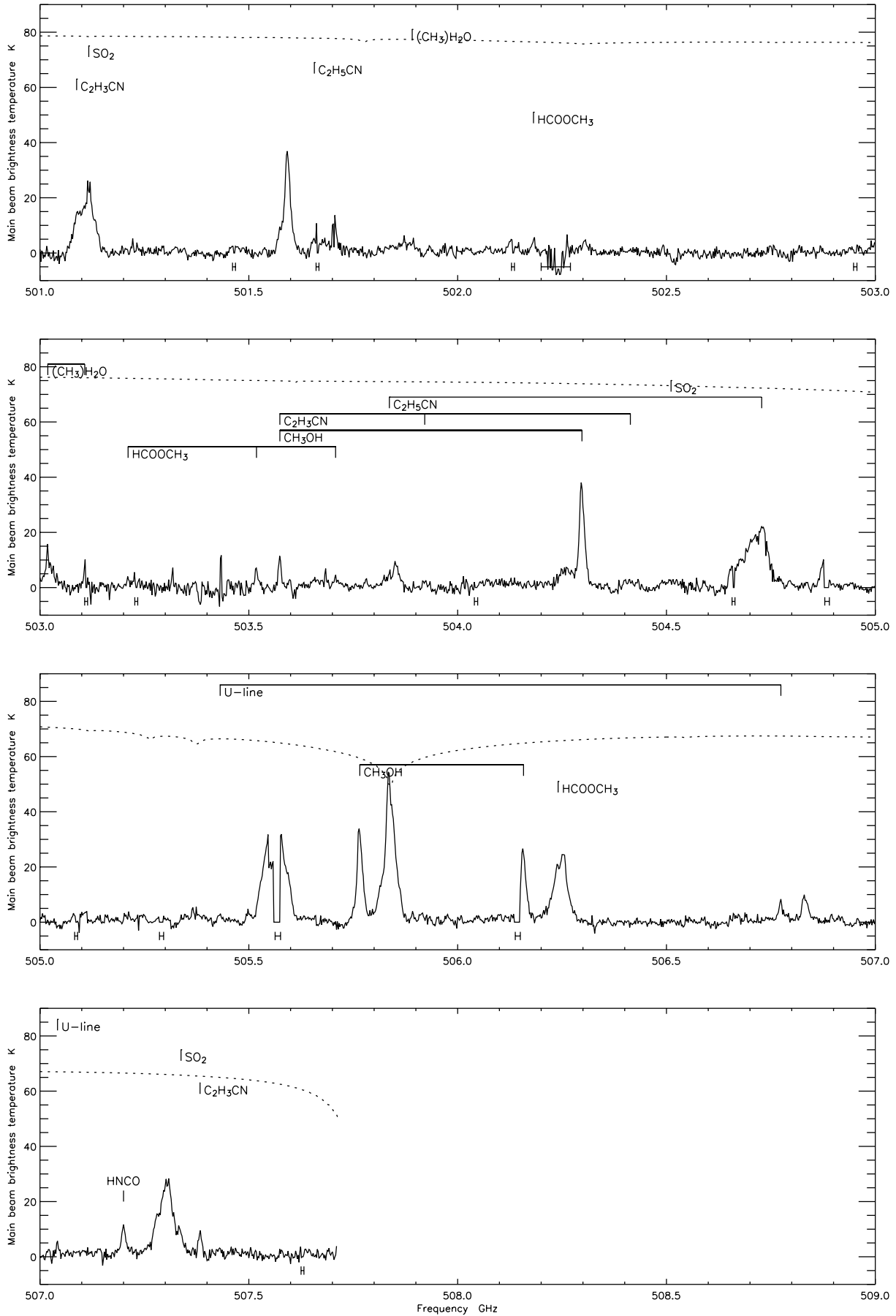


Fig. 6. Spectra and lines detected in the survey. The locations of parts of the spectra that were poorly deconvolved are indicated by horizontal lines placed underneath the spectrum.

Table 6. JCMT Orion spectral linesurvey.

Frequency MHz	Species	Transition	Peak T_{mb} K	Width km s ⁻¹	Vel km s ⁻¹	Notes
503.574370	C ₂ H ₃ CN	53 _{14,39/40} -52 _{14,38/39} $v = 0$	9.5	5.6	7.9	Blend with CH ₃ OH
503.574370	CH ₃ OH	7 ₆ -8 ₅	9.5	5.6	7.5	Blend with C ₂ H ₃ CN
503.707705	HCOOCH ₃	41 _{26,16} -40 _{26,15}	3.3	6.8	8.4	
503.836578	C ₂ H ₅ CN	28 _{6,23} -27 _{5,22}	3.4	2.1	6.8	
503.851690	SO	$N_J = 15_{14}$ -14 ₁₄	8.3	10.9	2.1	Blend with C ₂ H ₃ CN
503.921239	C ₂ H ₃ CN	29 _{6,24} -29 _{5,25} $v_2 = 1$	2.0	7.9	12.5	
504.297599	CH ₃ OH	7 ₁ -6 ₀	34.3	8.9	6.6	
504.413582	C ₂ H ₃ CN	23 _{6,17/18} -23 _{5,18/19} $v_2 = 1$	2.4	16.2	7.6	
504.510971	SO ₂	23 _{10,14} -24 _{9,15} +23 _{10,13} -24 _{9,16}	2.4	25.3	9.5	
504.680057	SO	$N_J = 4_3$ -1 ₂	9.3	26.7	6.8	
504.728059	³⁴ SO	$N_J = 12_{11}$ -11 ₁₀	20.5	22.4	6.6	Blend with C ₂ H ₅ CN
504.728059	C ₂ H ₅ CN	57 _{4,54} -56 _{4,53}	20.5	22.4	-0.6	Blend with ³⁴ SO
505.431404	U-line		2.7	7.7		
505.499853	C ₂ H ₅ OH	29 _{6,23} +28 _{6,22}	3.5	7.9	9.3	
505.765740	CH ₃ OH	10 ₂ -10 ₁	31.4	10.3	6.8	
505.838107	H ₂ CO	7 _{0,7} -6 _{0,6}	47.9	17.5	6.4	
506.157737	CH ₃ OH	11 ₁ -10 ₂	26.0	8.3	6.3	
506.240528	HCOOCH ₃	41 _{17,25/24} -40 _{17,24/23} +41 _{17,25/24} -40 _{17,23/24}	13.7	25.5	6.5	4 lines
506.253692	³⁴ SO	$N_J = 12_{12}$ -11 ₁₁	11.0	16.9	7.6	
506.773898	U-line		6.3	10.0		
506.831598	DCN	$J = 7-6$	8.7	11.8	6.6	
507.041856	U-line		4.5	5.9		
507.200247	HNCO	23 _{1,22} -22 _{1,21}	9.6	10.4	6.1	
507.301540	³⁴ SO	$N_J = 12_{13}$ -11 ₁₂	24.9	27.8	9.0	
507.337692	SO ₂	36 _{6,30} -35 _{5,31}	4.3	6.9	4.8	
507.383231	C ₂ H ₃ CN	27 _{3,24} -26 _{2,25} $v_1 = 1$	8.7	6.6	6.1	

form these molecules. The rotational temperature diagram for SO₂ (see Fig. 7) is consistent with previous estimates of the temperature and N_{col} . The temperature is 136 K, typical of the cooler conditions found in the plateau. The value of N_{col} is estimated to be $9.7 \times 10^{16} \text{ cm}^{-2}$ in the optically thin limit, increasing to $1.2 \times 10^{17} \text{ cm}^{-2}$ after making a correction for optical depth. Since our initial assumptions might be that this molecule should almost certainly be moderately optically thick, we ran a model, based on the Sutton et al. (1995) temperature and column density estimate, calculating the expected optical depths for the 35 SO₂ lines observed in this survey. One transition has a strong opacity $\tau = 1.46$. The optical depth of all other lines are less than 0.9 and for half of *all* the detected lines $\tau \leq 0.2$. Therefore the results of the optically thick and optically thin estimates of column density are understandably close to each other. This result is in reasonable agreement with studies using similar beam sizes, by Schilke et al. (2001) ($N_{\text{col}} = 9.7 \times 10^{16} \text{ cm}^{-2}$, $T \sim 187 \text{ K}$ for a 12–14'' beam) and Sutton et al. (1995) ($N_{\text{col}} = 9.4 \times 10^{16} \text{ cm}^{-2}$, $T \sim 99 \text{ K}$ for a 12–14'' beam).

We further estimate that the isotopic ratio $[\text{SO}_2]/[^{34}\text{SO}_2] = 14.1$, which is in agreement with previous estimates by Blake et al. (1987) (14–16) and Schloerb et al. 1983 (11).

4.3. Methyl cyanide (CH₃CN), ethyl cyanide (propionitrile) (C₂H₅CN), vinyl cyanide (acrylonitrile) C₂H₃CN

The $J = 25-24$ and $J = 27-26$ lines of methyl cyanide were observed at 459 and 495 GHz respectively. The average LSR velocity of the lines were $\sim 5.6 \text{ km s}^{-1}$ and the line widths $\sim 11 \text{ km s}^{-1}$. It is therefore likely that this species traces the hot core. The $J = 25-24$ $k = 7$ line (459.276 GHz) could not be assigned due to a strong U-line (459.267 GHz). Lines from the $J = 27-26$ $k = 2$ (-1) and $k = 3$ ($+1$) transitions were observed at 497.790 and 497.971 GHz respectively, although they were not used in the analysis due to their low intensities. The N_{col} and T_{rot} values for this molecule were $3.5 \times 10^{15} \text{ cm}^{-2}$ and $\sim 230 \text{ K}$ – similar to those estimated by Wilner et al. 1994; Sutton et al. 1995; Lee et al. (2001). Two lines of the isotopomeric variant CH₃¹³CN were also detected. No lines from the $v_8 = 1$ family were identified.

For this molecule, a) T_{rot} was fixed at 227 K, obtained from analysis of the CH₃CN line, and b) T_{rot} and N_{col} were calculated from the two observed lines. In this latter case, the value of T_{rot} is reduced to about one third that of CH₃CN. We consider that case a) provides a better solution, because of the difficulty

of estimating T_{rot} from two lines whose upper state energy levels are very similar to each other. It did not prove possible to identify the $J = 25-24$ $k = 0, 1, 3$ lines due to blending with CH_3CN . In view of the problems that have previously been encountered in the interpretation of CH_3CN lines using an optically thin assumption (Schilke et al. 1999; Comito et al. 2003), we ran a model to calculate the opacity of the various lines based on the above excitation conditions estimated by Wilner et al. (1994) (obtained with a similar beam size to our study). The largest value of τ amongst the present lines is estimated to be 0.2, and all other values were ≤ 0.1 . Making a correction for the optical depth only increases the value of column density by a few percent – from $N_{\text{col}} = 3.5 \times 10^{15} \text{ cm}^{-2}$ to $3.6 \times 10^{16} \text{ cm}^{-2}$. We therefore conclude that with few exceptions, the optically thin assumption provides a valid and useful estimate of column density for the transitions observed in this survey.

Thirteen lines of vinyl cyanide and its isotopomeric variant $\text{C}_2\text{H}_3\text{CN}$ were detected at LSR velocities consistent with the molecules being concentrated in the compact ridge. Line frequencies have been reported by Demaison et al. (1994). 5 lines were tentatively associated with the ν_{15} (out-of-plane bend) = 1 vibrational excited state. However, since the frequencies of the ν_{15} lines have a large error, they were not included in the fitting. We also searched at the expected frequency of the $\nu_{11} = 2$ state, but could not find convincing match. Grain surface reactions are thought to be the main process by which complex nitrogen bearing species are formed, due the high level of hydrogenation. It is not likely that a molecule such as CCCN would pick up the required number of hydrogen atoms to become ethyl cyanide without the intermediate step of adsorption on to a grain, allowing the hydrogenation process to occur. The high temperatures found in the hot core are sufficient to evaporate the molecules from the surface of any grains that drift into the region.

Twenty seven lines of ethyl cyanide were detected, based on line frequencies taken from Pearson et al. (1997) and Pearson (2000). It is expected that many observed lines of this molecule are blended with U-lines, and it was found that the simultaneous estimation of the column density and rotational temperature were difficult, since many of the lines are located very close together on the rotational diagram. To avoid this problem, we have calculated the column densities of $\text{C}_2\text{H}_5\text{CN}$ for two fixed temperatures, deriving values of $N_{\text{col}} = 2.4 \times 10^{16} \text{ cm}^{-2}$ (assuming a temperature of 150 K based on the work of Sutton et al. (1985), or $N_{\text{col}} = 8.3 \times 10^{15} \text{ cm}^{-2}$ (assuming a temperature of 239 K based on the work of Schilke et al. (2001)). As a result, the best estimates of the column density of the $\text{C}_2\text{H}_5\text{CN}$ from the present data are in the range $N_{\text{col}} = 2.4-0.83 \times 10^{16} \text{ cm}^{-2}$. This value is close to that estimated by Schilke et al. (2001) ($N_{\text{col}} = 3.1 \times 10^{16} \text{ cm}^{-2}$) with a beam size of $10-12''$ – which is very similar to that of the present survey. By comparison, Sutton et al. (1985) reported $N_{\text{col}} = 2 \times 10^{15} \text{ cm}^{-2}$ with a $30''$ beam. Assuming that the emitting region is a core with $10''$ diameter, $N_{\text{col}} = 1.5 \times 10^{16} \text{ cm}^{-2}$, which is in better agreement with the estimate in the present survey value. Similar arguments applied to the methyl cyanide line, to resolve the differences between the column densities from this survey, and the work of Blake et al. (1985) and

Schilke et al. (2001), again suggest that the size of the emitting region is $\sim 10''$.

4.4. Cyanamide (NH_2CN)

Three lines of NH_2CN were detected. However, it did not prove possible to obtain a reliable T_{rot} from the observed data. Consequently we assumed values of T_{rot} of 100 and 200 K, to make a first estimate of the column densities.

4.5. Carbonyl sulphide (OCS)

Two lines of OCS were detected. The fit for T_{rot} and N_{col} are not very accurate, since the upper state energy levels of the two lines are very similar.

4.6. Methylenimine (CH_2NH)

Methylenimine is a prolate asymmetric rotor with components of the electric dipole moment along both the a and b molecular axes, with magnitudes 1.325 and 1.53 D, respectively. The nitrogen nucleus produces electric quadrupole hyperfine structure in low-lying transitions. CH_2NH is a likely product following the UV irradiation of icy interstellar grain mantles and may be a precursor of other complex organics which may be present in cometary ices (Bernstein et al. 1995), and may be a precursor to glycinenitrile and glycine (e.g., Dickerson 1978). Three lines of CH_2NH were used in the fitting. It was considered likely that the $2_{2,1}-2_{1,2}$ line was probably blended with a U-line, since the intensity was strong compared with the other two lines.

Using only two lines, it did not prove possible to get a reasonable value for T_{rot} . Hence, in fitting the value of T_{rot} was fixed at 150 K, from observations of HNCO , which has a similar dipole moment (CH_2NH $\mu(a) = 1.352 \text{ D}$, $\mu(b) = 1.530 \text{ D}$, HNCO $\mu(a) = 1.602 \text{ D}$, $\mu(b) = 1.35 \text{ D}$ – from Kirchoff et al. 1973; Hocking et al. 1975). The derived column density, $N_{\text{col}} = 2.4 \times 10^{15} \pm 1.8 \times 10^{14} \text{ cm}^{-2}$, is in reasonable agreement with the column density reported in the detection paper by Dickens et al. (1977) of $N_{\text{col}} = 6.2 \pm 1.8 \times 10^{14} \text{ cm}^{-2}$, based on observations of 5 transitions (three of which were blended with other lines) between 172 and 256 GHz obtained with a larger beam of $23-34''$.

4.7. Methanol (CH_3OH) and ethanol ($\text{C}_2\text{H}_5\text{OH}$)

Methanol, CH_3OH , is one of the most widely observed molecules in star forming regions. Line frequencies are reported by Xu & Lovas (1997). Twenty four CH_3OH lines were detected with an average velocity of 7.8 km s^{-1} and line width of 9.9 km s^{-1} – suggesting that it is likely to be excited in the compact ridge. The high observed abundances of this molecule imply a high abundance of the precursor ion CH_3^+ which would react with water in a ion-molecule process to form methanol. Two lines of $^{13}\text{CH}_3\text{OH}$ (which were apparently detected at 492.695 and 498.677 GHz) would indicate that the main methanol line may have an opacity of at least 0.7.

Schilke et al. (2001) have pointed out the difficulty of applying simple rotational analysis techniques to methanol due to opacity problems. The column densities reported in Table 1 have been should therefore be treated as lower limits. If the 498.677 GHz line is assigned to $^{13}\text{CH}_3\text{OH-A}(8_2-8_1)$, the column density of this molecule would be $8.7 \times 10^{15} \text{ cm}^{-2}$ assuming the rotational temperature is the same as that of $^{12}\text{CH}_3\text{OH}$ (600 K – but note that the error on this is 50%). This would indicate that the $[^{12}\text{C}]/[^{13}\text{C}]$ ratio ~ 10 – although this would also decrease if the temperature were substantially less than 600 K. Neither the $^{13}\text{CH}_3\text{OH-E}(23_2-23_1)$ line at 503.216 GHz, nor any lines of torsionally excited methanol were identified.

Eight lines of $\text{C}_2\text{H}_5\text{OH}$ were detected, at a velocity of $\sim 8 \text{ km s}^{-1}$, although only 6 were used in the rotational temperature fitting. Line frequencies are given by Pearson et al. (1996). The lines at 494.899 and 495.821 had line widths that were too broad and narrow respectively, and it is likely that these are blended, or due to other species. For this molecule, we made two fits; a) simultaneously fitting both N_{col} and T_{rot} , and b) T_{rot} was fixed at 70 K (following Ohishi et al. 1995), since simultaneous fitting of both T_{rot} and N_{col} led to large uncertainties, and a large T_{rot} .

4.8. Methyl formate (HCOOCH_3)

The line widths and velocities of the HCOOCH_3 lines suggest an origin in the compact ridge. Line frequencies are given by Osterling et al. (1999). Lines are seen from both the E- and the A-symmetry states. The high abundance follows directly from the high abundance of methanol whose precursor ion CH_3OH_2^+ reacts with H_2CO . The column density we derive is similar to that estimated by Schilke et al. (1997), who have discussed difficulties in assigning an unique rotation temperature for this line.

4.9. Dimethyl ether ($(\text{CH}_3)_2\text{O}$)

Dimethyl Ether, $(\text{CH}_3)_2\text{O}$, is one of the few interstellar molecules whose emission lines are affected by the presence of two internal rotors. Line frequencies are reported by Groner et al. (1998). Twenty seven lines were detected in this survey, which were best described by a fit of $N_{\text{col}} = 1.4 \times 10^{16} \text{ cm}^{-2}$ and $T_{\text{rot}} = 157 \text{ K}$ for the column density and rotational temperature respectively. These values are close to those found by Sutton et al (1985) toward the compact ridge. The line widths and velocities are consistent with an origin in the compact ridge. The fact that this molecule appears to be far more abundant (from the large number of strong lines) than ethanol leads to the conclusion that the Compact ridge, where these molecules are formed, is rich in hydrogen. The molecule is formed by a similar method to methyl formate except that CH_3OH_2^+ reacts with methanol to form it.

4.10. Formaldehyde (H_2CO)

H_2CO is a highly prolate asymmetric top molecule. The rotational temperature of H_2CO was fixed at 166 K following

Blake et al. (1987). Two lines were associated with this molecule, however an additional line at 491.979 GHz was not included in the fitting, since its velocity appeared to be low (2.6 km s^{-1}). The derived column density is very similar to that estimated by Blake et al. (1987).

4.11. Deuterated water (HDO)

A single transition of HDO was detected at 464.925 GHz. It has a clear hot core line shape with a line width of 16.2 km s^{-1} and a velocity of 6.6 km s^{-1} . We have attempted to model this line along with the two other lines reported and analysed by Schulz et al. (1991) and Sutton et al. (1985). Pardo et al. (2001b) have recently reported detections of the $J_{\text{Ka,Kb}} = 2_{1,2}-1_{1,1}$ and $1_{1,1}-0_{0,0}$ lines in the 850–900 GHz region, which appear to trace the plateau gas, rather than the hot core material which contributes rather more to the other HDO lines observed to date. We therefore estimate values of $3.2 \times 10^{16} \text{ cm}^{-2}$ and 164 K for N_{col} and T_{rot} respectively, in broad agreement with values reported by Plambeck & Wright (1987) and Jacq et al. (1990). This is as expected from the high abundances observed for molecules such as methanol and methyl formate which require water to be present for their formation. It is thought that both water and deuterated water are formed elsewhere on grains and evaporated from the surfaces in the higher temperature conditions found in the hot core (Beckman et al. 1981; Pardo et al. 2001b).

4.12. Atomic carbon (CI)

A lower limit on the column density of the $\text{CI } ^3\text{P}_1 - ^3\text{P}_0$ transition was determined with the treatment of the optically thin line emission given by White & Sandell (1995). The column density, $N_{\text{col}} = 1.2 \times 10^{18} \text{ cm}^{-2}$ is consistent with that of White & Sandell (1995). Keene et al. (1998) detected the ^{13}CI line toward a position 4' south of our pointing position, showing that the main isotopomeric line was optically thin. Consequently we have used the optically thin column density estimate.

4.13. Other molecules

Other detections that are of interest include HCCCN and HNCO (Isocyanic Acid), both with line shapes are typical of the hot core, and with estimated abundance similar to those reported by Schilke et al. (1997).

4.14. Unidentified lines

At total of 33 lines were detected that could not be associated with known spectral lines. We searched carefully in the Cologne Database for Molecular Spectroscopy (Müller et al. 2001) and the JPL Molecular Spectroscopy Database, as well as other tables of isotopomeric variants of lines that were present in the survey (e.g. CH_3OH and $^{13}\text{CH}_3\text{OH}$ from the laboratory measurements of Anderson et al. 1987, 1990, 1992). Although there were inevitably a number of lines that lay close

to some of the U-line frequencies, we also used secondary criteria (line strength predictions from the Cologne database, upper energy state levels, and the presence or absence of other lines from similar levels) to make judgments as to whether lines could be associated with particular species. Six lines that were originally designated as U-lines were associated in this way, however a substantial number of intense lines remain. Assignment of lines to these frequencies is beyond the scope of this paper, and will require a sophisticated modeling effort, combined with U-lines from other published surveys. We note that the number of U-lines inferred from the present survey (33 - or 13% of the total) is similar reported from some other surveys (325–360 GHz \sim 8% Sutton et al. 1995), 607–725 GHz \sim 14% (Comito et al. 2003).

4.15. Notes on T_{rot} diagrams

Plots used to fit the estimates of T_{rot} or N_{col} are shown in Fig. 7.

The values for the intrinsic line strengths, level degeneracies and partition functions are derived from the literature, including the spectral line catalogues cited previously (see also Eqs. (1) and (2)).

4.16. Line-to-continuum ratio

The data may also be used to estimate the ratio of line-to-continuum emission from the source. This is an important value to characterise for a range of molecular clouds – since a considerable fraction of the fluxes measured with submm continuum cameras, such as the JCMT’s SCUBA, and the CSO’s SHARC, may be due to the integrated line emission, rather than thermal dust. Early attempts to measure, or characterise this ratio toward Orion have included the work of Groesbeck (1995), Greaves & White (1991), White & Sandell (1995), Schilke et al. (1997, 2001). The integrated line emission of the spectrum shown in Fig 1 is $\sim 1.1 \times 10^5$ K MHz. The *average* rms noise level over the whole survey range was 1.5 K per 2 MHz channel, and therefore line emission would not be detected under this level. If lines of this strength were uniformly spread across the 30 GHz spectral range, then this would contribute a further $\sim 4.5 \times 10^4$ K MHz to the integrated line emission. The total estimated integrated emission corresponds to an integrated main beam temperature of 3.7 K MHz $^{-1}$. Greaves & White (1991) reported an integrated emission of $\sim 1.0 \times 10^4$ K MHz over a total range of 16 GHz, which corresponded to an average temperature of 0.6 K MHz $^{-1}$ – or about one sixth of that estimated here. This discrepancy can partially be explained by the fact that the hot core is smaller in angular extent than the beam size used in both this and the survey of Greaves & White (1991). The coupling efficiency η_c to a Gaussian source of radius σ_s is given by:

$$\eta_c = \frac{\sigma_s^2}{(\sigma_s^2 + \sigma^2)} \quad (3)$$

where σ is the Gaussian radius of the telescope beam. Taking $\sigma_s = 4''$ and $\sigma = 4.2''$ (for a 10'' FWHM beam), $\eta_c = 0.48$, and $\eta_c = 0.25$ for the survey of Greaves & White (1991) would

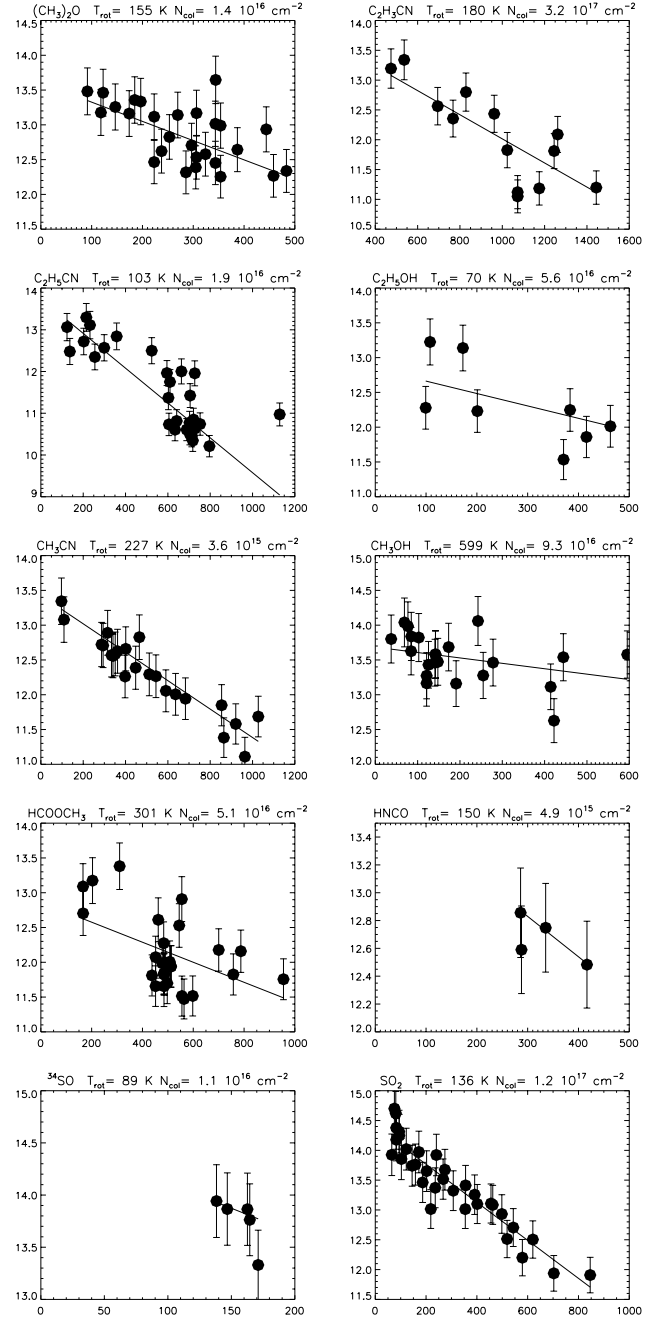


Fig. 7. Rotational temperature diagrams. The fitted lines were derived from a noise-weighted least squares fitting procedure.

lead to an expectation that the current value should be double that previously estimated for this reason. The lower beam dilution in this survey could explain the rest of the discrepancy. No measurements of the continuum emission exist for the exact frequency that this survey was conducted at, but by using the measurements made by White & Sandell (1995) at 790 μm it is possible to extrapolate and make an estimate of the emission at 600 μm (500 GHz). The spectral index was estimated by White & Sandell (1995) to be 1.5 and the emission was 134.9 Jy in a 10'' beam with an aperture efficiency of 0.3. The antenna temperature (T_A) is given by:

$$kT_A = \frac{1}{2} \eta_R \eta_A S_\nu A \quad (4)$$

where k is the Boltzmann constant, η_A is the aperture efficiency (0.3 for these observations), η_R is the resolution correction and A is the effective area of the antenna. This equation yields a value $T_A = 6.8\text{K}$. Correcting this value for sideband gains, atmospheric emission and main beam efficiency gives $T_{\text{mb}} = 14.4\text{ K}$. This means that the line to continuum ratio at 500 GHz is $3.7 \div 14.4 = 0.25$. This lies between the value of 10% found by Greaves & White (1991) and 30–40% found by Sutton et al. (1985) at lower frequencies. We stress that this value is the best estimate lower limit to the line-to-continuum ratio that can be made with the present data – a further measurement that simultaneously measures the continuum and line flux is desirable to obtain a more accurate value – and would for example be valuable when trying to understand the relative contributions of thermal and line emission observed at far infrared wavelengths by bolometer detectors, and far-IR fourier transform spectrometers. The value we have estimated is consistent with the prediction given by Groesbeck (1995 – also reported in Schilke et al. 2001) that the contribution of line emission to the total flux of Orion should drop from $\sim 50\%$ at $800\text{ }\mu\text{m}$ to 10% at $450\text{ }\mu\text{m}$.

5. Conclusions

A spectral line survey of the hot core region of the OMC-1 cloud core was obtained over the frequency intervals 455–468 GHz and from 491.8–507.4 GHz.

- In this spectral line survey we find a total of 254 lines toward the hot core position at the centre of the Orion Nebula.
- Spectral lines of SO, SO₂ and CH₃OH and from large organic molecules such as (CH₃)₂O, CH₃CN, C₂H₅CN, HCOOCH₃ and C₂H₃CN make up $\sim 72\%$ of the total number of lines
- A total of 33 lines (13% of the total lines identified) could not be associated with known molecular transitions and are designated U-lines – this is comparable to the percentages of U-lines seen in other spectral lines surveys of Orion.
- The rotational temperatures and column densities derived using standard rotation diagram analysis techniques, showed ranges from 70–300 K, and 10^{14} – 10^{17} cm^{-2} respectively (we exclude the CH₃OH line from this, as the error is large).
- The diameter of the region responsible for emitting the C₂H₅CN and C₂H₃CN lines is estimated to be $\sim 10''$, based on a comparison with earlier data for the same lines.
- The lower limit to the line-to-continuum ratio from the hot core region is 0.25, which appears to be consistent with predictions based on modeling the expected intensities of lines from the JPL Molecular Spectroscopy database.

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References

- Anderson, T., Herbst, E., & de Lucia, F. 1987, *ApJS*, 64, 703
 Anderson, T., Herbst, E., & de Lucia, F. 1990, *ApJS*, 74, 647
 Anderson, T., Herbst, E., & de Lucia, F. 1992, *ApJS*, 82, 405
 Beckman, J. E., Watt, G. D., White, G. J., et al. 1981, *MNRAS*, 201, 357.
 Blake, G. A., Masson, C. R., Phillips, T. G., et al. 1986, *ApJS*, 60, 357
 Bernstein, M. P., Sandford, S. A., Allamandola, L. J., Chang, S., & Scharberg, M. A. 1995, *ApJ*, 454, 327
 Comito, C., Schilke, P., Lis, D. C., et al. 2002, *SFCHEM 2002: Chemistry as a Diagnostic of Star Formation*, proceedings of a conference held August 21–23, 2002 at University of Waterloo, Waterloo, Ontario, Canada N2L 3G1, ed. C. L. Curry, & M. Fich (Ottawa, Canada: NRC Press), 18
 Dickens, J. E., Irvine, W. M., De Vries, C. H., & Ohishi, M. 1997, *ApJ*, 479, 307
 Demaison, J., Cosleou, J., Bocquet, R., & Lesarri, A. G. 1994, *J. Mol. Spect.*, 167, 400
 Blake, G., Sutton, E., Masson, C., et al. 1987, *ApJ*, 315, 621 (Bla87)
 Goldsmith, P. F., & Langer, W. D. 1999, *ApJ*, 517, 209
 Greaves, J. S. 1990, Ph.D. Thesis, University of London
 Greaves, J. S., & White, G. J. 1991, *A&AS*, 91, 237
 Groesbeck, T. D. 1995, Ph.D. Thesis, Caltech
 Groner, P., Albert, S., Herbst, E., & De Lucia, F. C. 1998, *ApJ*, 500, 1059
 Hasegawa, T. 1986, *Ap&SS*, 118, 421
 Hermsen, W., Wilson, T. L., Walmsley, C. M., & Henkel, C. 1988, *A&A*, 201, 285 (Her88)
 Hocking, W. H., Gerry, M. C. L., & Winnewisser, G. 1975, *Can. J. Phys.*, 53, 1869
 Jacq, T., Walmsley, C. M., Mauersberger, R., et al. 1990, *A&A*, 228, 447
 Jewell, P. R., Hollis, J. M., Lovas, F., et al. 1989, *ApJS*, 70, 833
 Johansson, L. E. B., Andersson, C., Ellder, J., et al. 1984, *A&A*, 130, 227
 Keene, J., Schilke, P., Kooi, J., et al. 1998, *ApJ*, 494, L107
 Kirchhoff, W. H., Johnson, D. R., & Lovas, F. J. 1973, *J. Phys. Chem. Ref. Data*, 2, 1
 Lee, C. W., Cho, S.-H., & Lee, S.-M. 2001, *ApJ*, 551, 333
 Lepp, S., & Delgarno, A. 1988, *ApJ*, 324, 553
 Müller, H. S. P., Thorwirth, S., Rothe, D. A., et al. 2001, *A&A*, 370, L49 (and a searchable internet form at the URL: <http://www.ph1.uni-koeln.de/vorhersagen/>)
 Naylor, D. A., Davis, G. R., Gom, B. G., et al. 2000, *MNRAS*, 315, 622
 Nummelin, A., Bergman, P., Hjalmarson, A., et al. 2000, *ApJ*, 128, L213
 Ohishi, M., Ishikawa, S., Yamamoto, S., et al. 1995, *ApJ*, 446, L43 (Ohi95)
 Oesterling, L. C., Albert, S., De Lucia, F. C., Sastry, K. V. L. N., & Herbst, E. 1999, *ApJ*, 521, 255
 Padman, R., White, G. J., et al. 1992, *Int. Journ. IR and Mm Waves*, 13, 10
 Pardo, J. R., Serabyn, E., & Cernicharo, J. 2001, *JQSRT*, 68, 419
 Pardo, J. R., Cernicharo, J., Herpin, F., et al. 2001, *ApJ*, 562, 799
 Pearson, J. C., Sastry, K. V. L. N., Herbst, E., & De Lucia, F. J. 1996, *J. Mol. Spect.*, 175, 246
 Pearson, J. C., Sastry, K. V. L. N., Herbst, E., & De Lucia, F. J. 1997, *ApJ*, 480, 420
 Pearson, J. C. 2000, Private communication
 Pickett, H. M., Poyner, R. L., & Cohen, E. A. 1995, *Submillimeter, Millimeter, and Microwave Spectral line Catalogue*, on the World Wide Web (<http://spec.jpl.nasa.gov>)

- Plambeck, R. L., & Wright, M. C. H. 1987, *ApJ*, 317, L101
- Prasad, S. S., & Huntress, W. T. 1982, *ApJ*, 260, 590
- Schilke, P., Groesbeck, T. D., Blake, G. A., & Phillips, T. G. 1997, *ApJS*, 108, 301 (Sch97)
- Schilke, P., Phillips, T. G., & Mehringer, D. M. 1999, in *The Physics and Chemistry of Interstellar Medium*, Proc. 3rd Cologne-Zermatt Symposium, ed. V. Ossenkopf, J. Stutzki, & Winnewisser, p. 330
- Schilke, P., Benford, D. J., Hunter, T. R., Lis, D. C., & Phillips, T. G. 2001, *ApJS*, 132, 281 (Sch01)
- Schloerb, F. P., Irvine, W. M., Friberg, P., Hjalmarsen, A., & Hoglund, B. 1983, *ApJ*, 264, 161
- Schulz, A., Güsten, R., Walmsley, C. M., & Serabyn, E. 1991, *A&A*, 246, L55
- Serabyn, E., & Weissstein, E. W. 1995, *ApJ*, 451, 238
- Sutton, C., Blake, G., Masson, C., & Phillips, T. G. 1985, *ApJS*, 58, 341 (Sut85)
- Sutton, E. C., Peng, R., Danchi, W. C., et al. 1995, *ApJS*, 97, 455 (Sut95)
- Turner, B. E. 1991, *A&AS*, 76, 617
- Turner, B. E. 1989, *ApJS*, 70, 539
- White, G. J., Griffin, M. J., Rainey, R., et al. 1986, *A&A*, 162, 253
- White, G. J., & Sandell, G. 1995, *A&A*, 299, 179 (Whi95)
- White, G. J., & Padman, R. 1991, *Nature*, 354, 511
- Wilner, D. J., Wright, M. C. H., & Plambeck, R. L. 1994, *ApJ*, 422, 642
- Wright, M. C. H., Plambeck, R. L., Vogel, S. N., et al. 1983, *ApJ*, 267, L41 (Wri83)
- Zeng, Q., & Pei, C. C. 1995, *Ap&SS*, 229, 301 (Zen95)
- Ziurys, L. M., & McGonagle, D. 1993, *ApJS*, 89, 155
- Xu, L.-H., & Lovas, F. J. 1997, *J. Phys. Chem. Ref. Data*, 26, 17